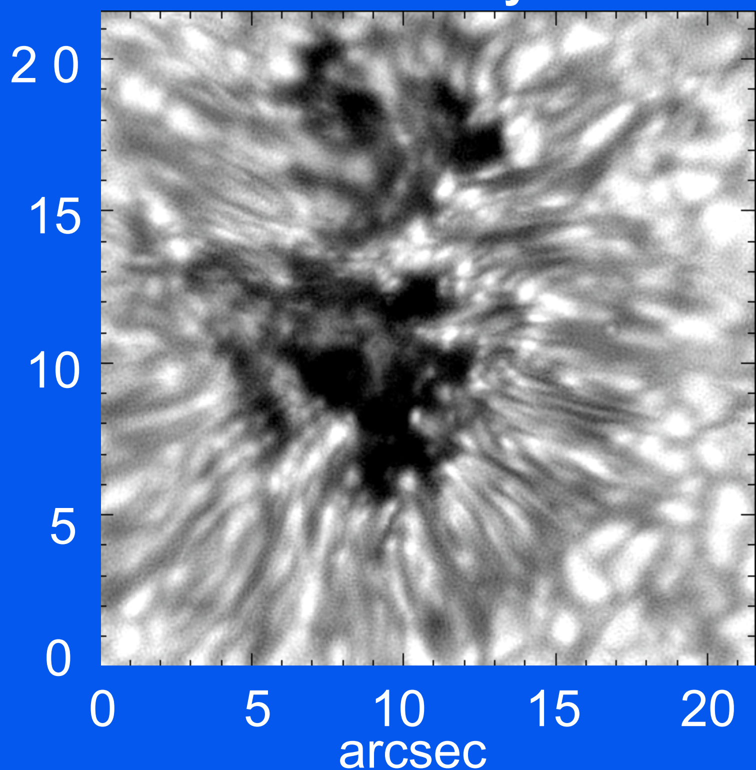
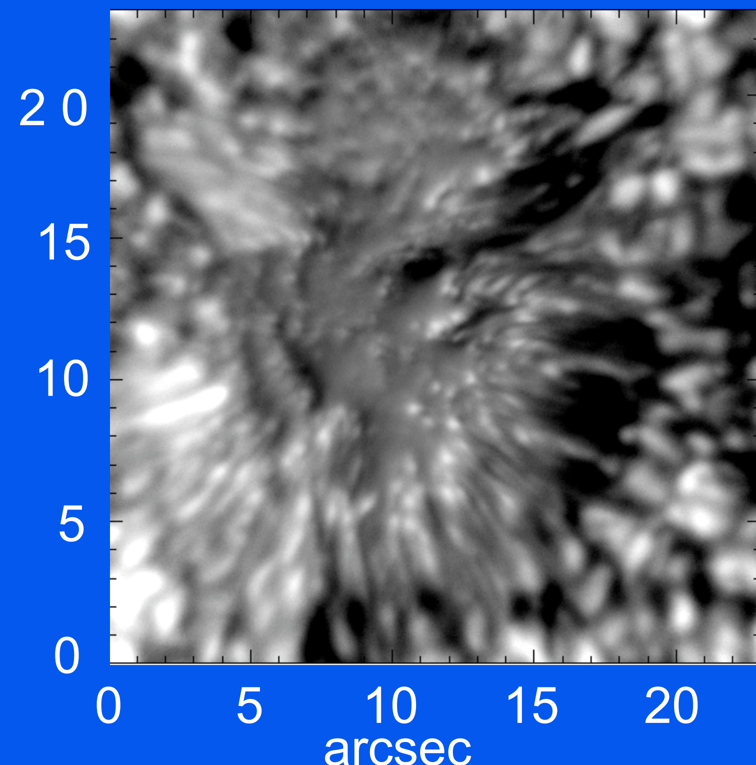
The Advanced Solar Telescope

Stephen L. Keil, Thomas Rimmele, Christoph Keller

Intensity



Velocities



Diffraction limited Images (0.15”) taken with the 76 cm Dunn Solar Telescope using low-order (24 degrees of freedom) adaptive optics.

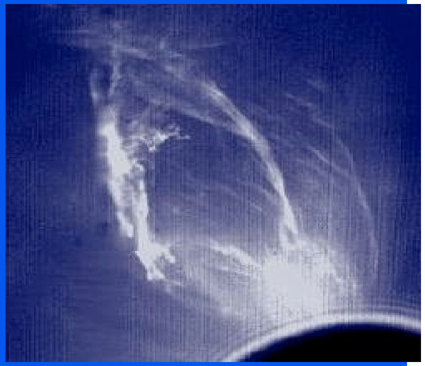
The AST is envisioned as a 4m aperture telescope that will for the first time resolve the tiny features seen in these images.

Advanced Solar Telescope

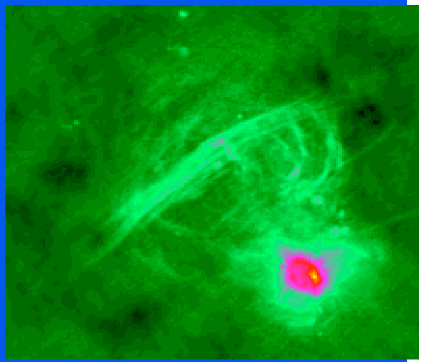
Science Goals

- **Addresses Broad Scientific Questions**
  - **How are cosmic magnetic fields generated and how are they destroyed?**
  - **What role do cosmic magnetic fields play in the organization of plasma structures and the impulsive releases of energy seen ubiquitously in the universe?**
  - **What are the mechanisms responsible for solar variability (that ultimately affects the Earth)?**
  - **What can we learn about modeling and controlling laboratory Plasma?**

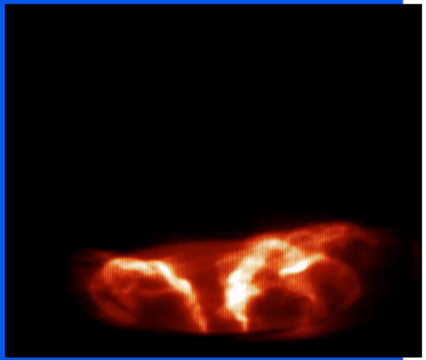
Erupting Prominence
(HAO)



Radio Map of Galactic Center
(NRAO)



Spheromak Reaction
(Paul Bellan, Cal Tech)



Advanced Solar Telescope

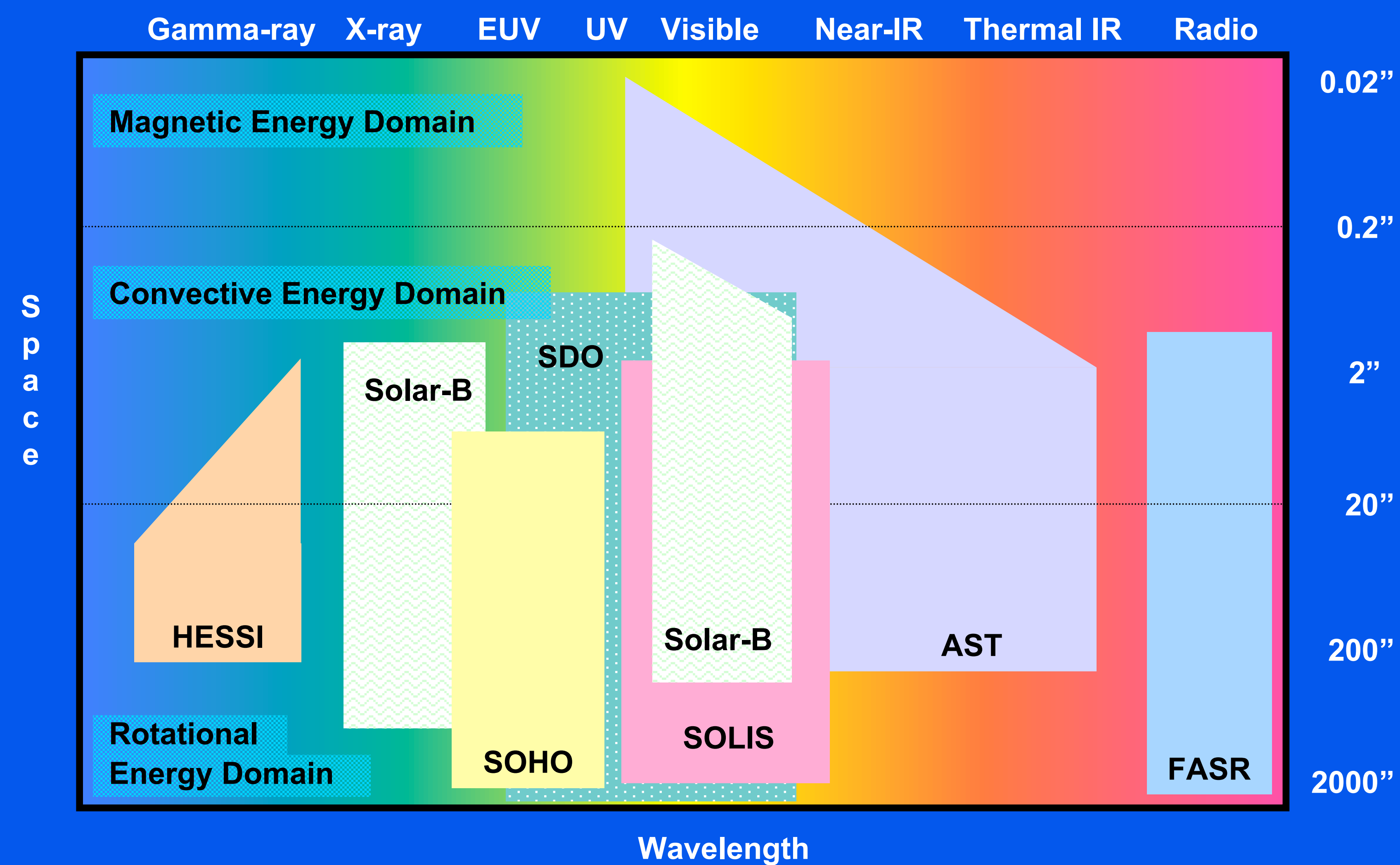
AST and LWS

- **AST Is a NSF Initiative That Will Complement LWS Missions**
  - **Extend Wavelength Coverage to Thermal IR**
  - **Extend Spatial Resolution Below 0.1”**
  - **Provide Rapid Cadence Polarimetry of Active Regions**
  - **Provide Instrument Flexibility & Larger Set of Science Objectives**

- **AST Will Be Operated Simultaneously With Missions Like SDO**
  - **SDO Has Large FOV and Provides Connections Between Surface Activity and the Outer Solar Atmosphere and the Interplanetary Space**
  - **AST Has Small Field of View but Provides the Critical Small-scale Physics of Magnetic Filed-plasma Interactions**
  - **AST Can Provide Follow-on Observations With Rapid Changes in Focal Plane Instrumentation**

Advanced Solar Telescope

Spatial vs Wavelength Coverage



Advanced Solar Telescope

Science Drivers

Transient eruptions: flares and coronal mass ejections

IMPACT
- understand sources of space weather
- understand origin of interstellar matter
- understand stellar flares

Origin of solar variability

IMPACT
- understand solar input to global change
- understand irradiance variation of solar-like stars

Heating of chromosphere and corona, origin of solar wind

IMPACT
- understand origin and heating of upper stellar atmospheres
- understand accretion disk coronae

Surface and atmosphere structure and dynamics

IMPACT
- understand basic MHD processes
- understand excitation of stellar p-mode oscillations

Exploring the unknown

IMPACT
- open new windows
- provide best solar telescope in the world

High Spatial Resolution

High Photon Flux

Thermal Infrared

Advanced Solar Telescope

Design Drivers

- Basic Telescope Parameters
  - An Angular Resolution of 0.1 Arcsec or Better to Resolve the Pressure Scale Height and the Photon Mean Free Path
  - A High Photon Flux at the Critical Spatial Resolution for Precise Magnetic and Velocity Field Measurements
  - Access to a Broad Set of Diagnostics, 0.3 to 35 μM
- Technology Requirements
  - Functioning Solar Adaptive Optics Systems in the Visible
  - An Open-air Solar Telescope That Provides Diffraction Limited Images
  - Large-format Infrared Cameras

Advanced Solar Telescope

AST Design Drivers

4 m all reflective telescope with adaptive optics

provides high spatial resolution

resolve fundamental physical scale of 70 km

provides high photon flux

structure & dynamics of ubiquitous magnetic fields

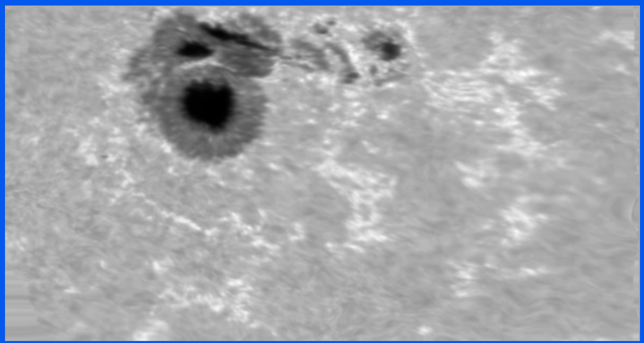
provides access to thermal infrared

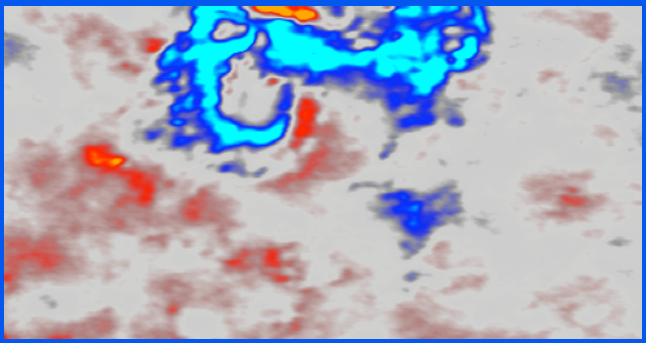
resolve temperature inhomogeneities in chromosphere

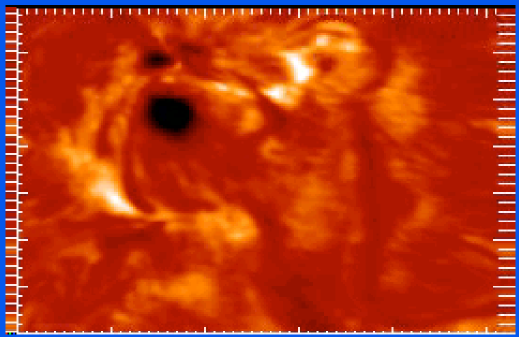
Advanced Solar Telescope

High Spatial Resolution

- Convection
  - Shocks, Vortices, Interaction With Magnetic Flux
  - Build-Up of Energy in Active Regions
  - Generation of 5-minute Oscillations
- Waves and Oscillations in Flux Tubes
  - Role of Flux Tubes in Heating the Upper Chromosphere and Corona
- Need to Understand General Flux Loss for Dynamo
  - Rate of Emergence
  - How Much Cancellation
  - How Much Is Ejected



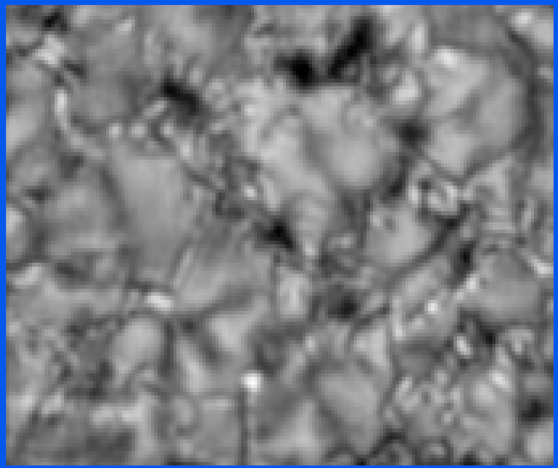


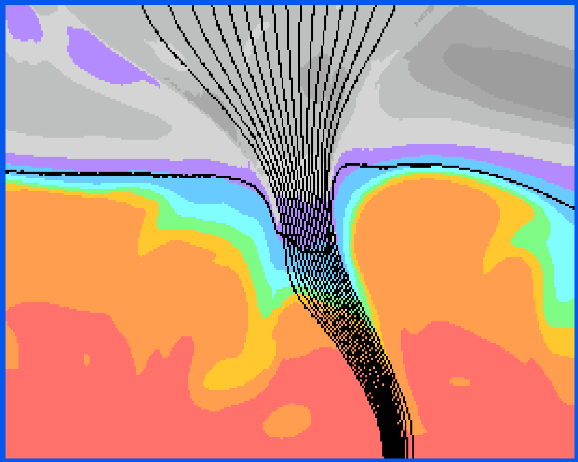


Advanced Solar Telescope

Interaction of Magnetic Fields and Mass Flows

- **Importance of Flux Tubes:**
  - **Building Blocks of Strong Magnetic Fields**
  - **Most Likely Channels for Transporting Energy to the Upper Atmosphere**
  - **Affect Convection, Total Irradiance, Oscillations, Solar Cycle**
- **Need to Spatially Resolve These Structures**
- **To Learn: Structure, Dynamics, Connection to Higher Layers, Brightness, Energizing by Convection, Waves**





Courtesy Oskar Steiner

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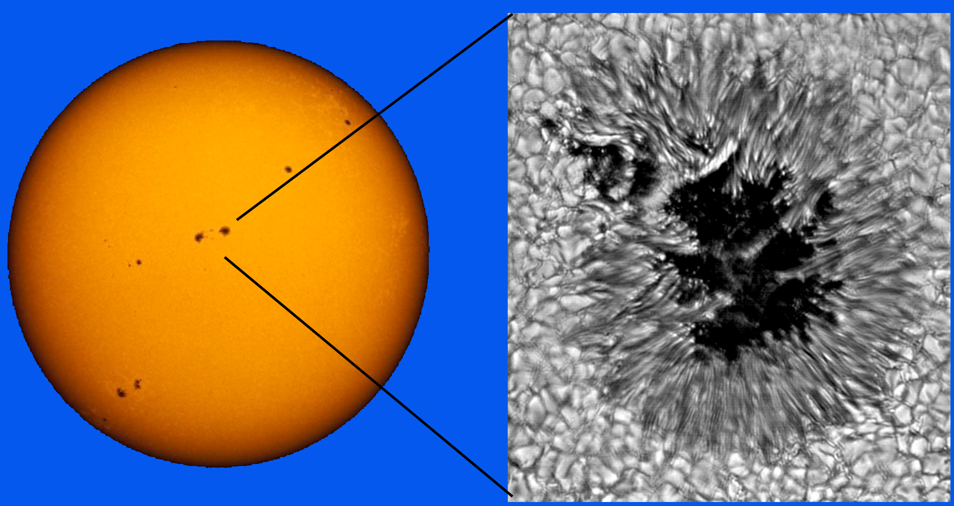
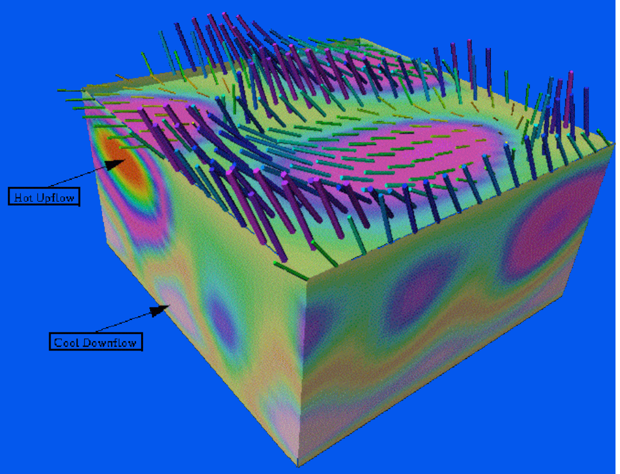
Interaction of Magnetic Fields and Mass Flows

- **Sunspots**
  - **Magnetic Field dominates the hydrodynamic behavior**
  - **Magneto-convection in Umbral Dots and Penumbral Filaments**
  - **Combed Penumbral Fields, Evershed Effect**
  - **Snapshots Not Enough, Need Spectroscopy**
  - **Relevance to Other Stars With Huge Spots**



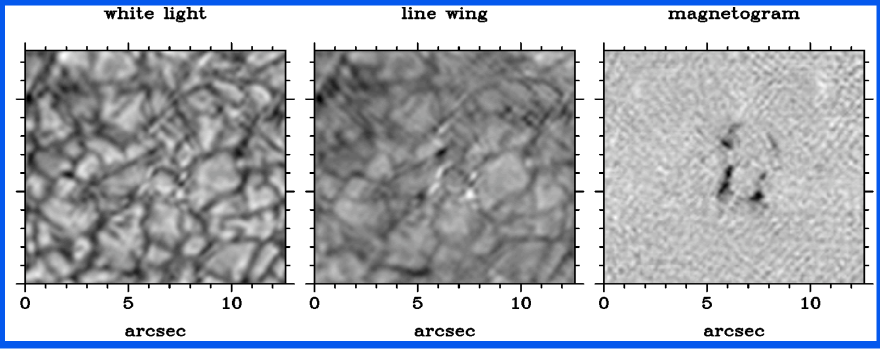
AST



Advanced Solar Telescope

Waves & Oscillations in Flux Tubes

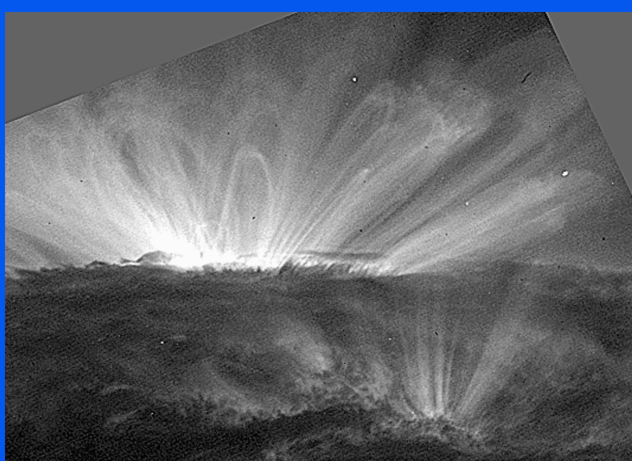
- **Goal:** To Understand the Role of Flux Tubes in Heating the Upper Chromosphere and Corona
- **Current State**
  - **Speckle Polarimetry Resolves Large Flux Tubes**
  - **Sophisticated MHD Models Exist**
  - **No Spectroscopy of Individual Flux Tubes**
  - **Lack of Spatial Resolution and Photons**
- **Future Direction**
  - **Perform Spectroscopy, Vector Polarimetry of Individual Flux Tubes With High Temporal Resolution**
  - **Need Large Telescope With Adaptive Optics**



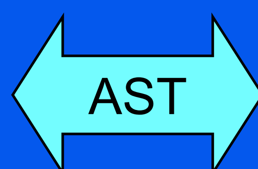
Advanced Solar Telescope

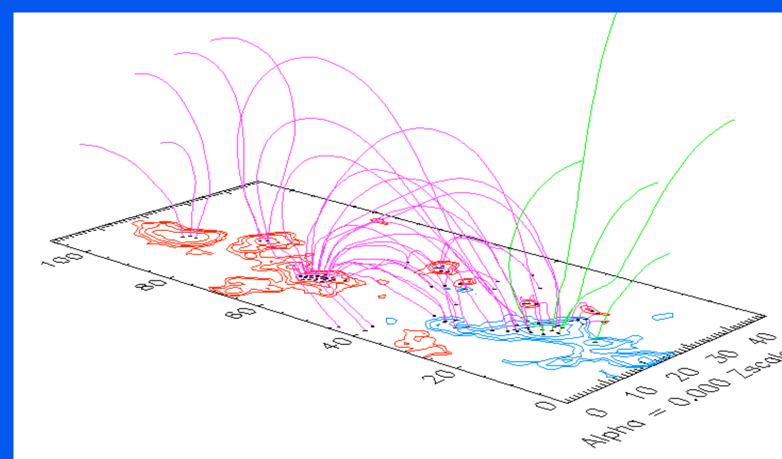
High Photon Flux

- Origins of Solar and Stellar Coronae
  - Magnetic Fields Rooted at the 0.1” Scale in the Photosphere
  - EUV and X-ray Observations Reveal Small-scale Coronal Structure
  - Ground-based Needed to Determine Photospheric Forcing and Coronal Magnetic Field Strength
- Feasible to Measure Coronal Fields With the AST
  - In IR Where Scattered Light Is More Easily Controlled
  - Test Models of Flares and Coronal Mass Ejections



Data courtesy A. Title (TRACE)





Meudon Observatory

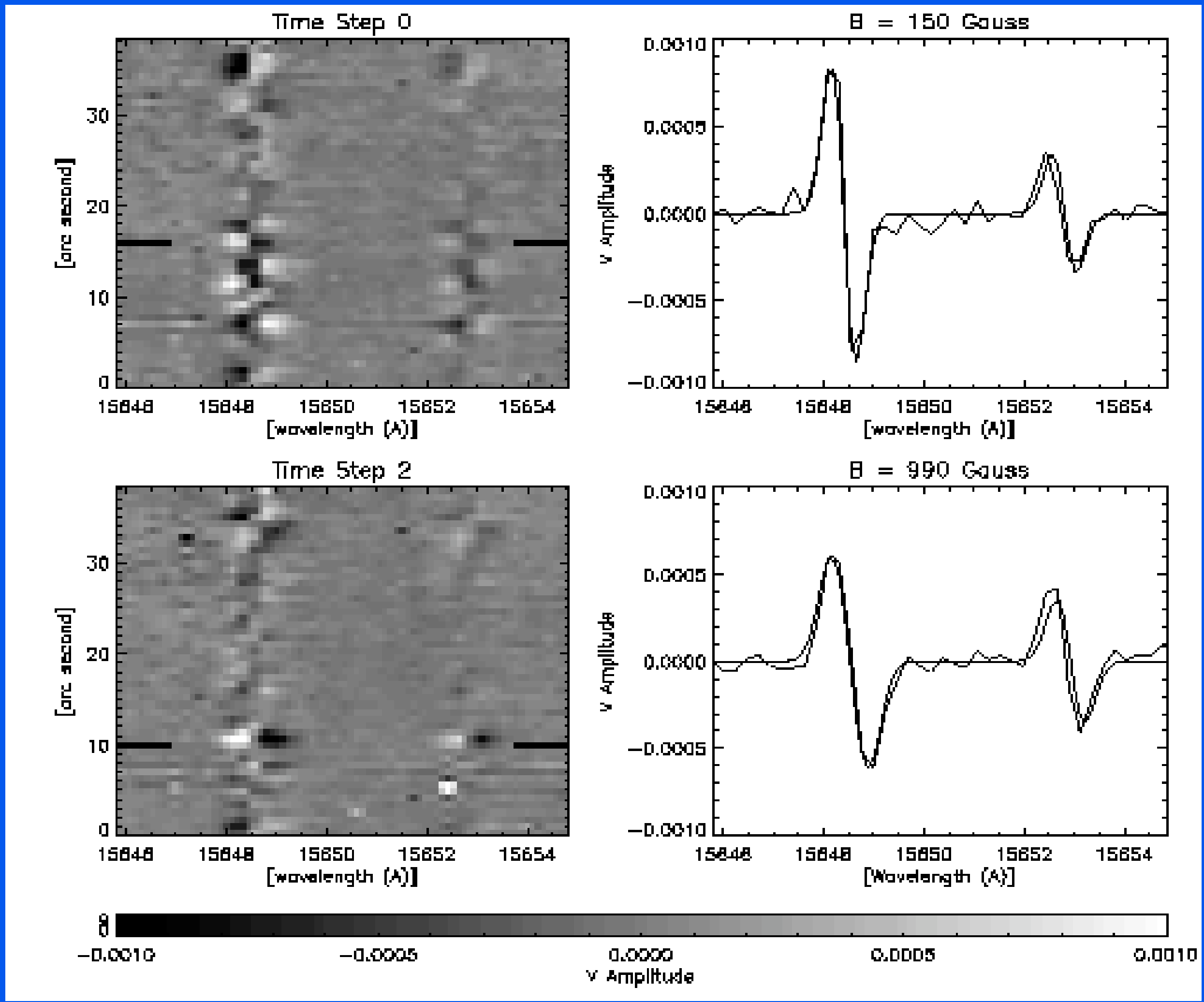
Advanced Solar Telescope

High Photon Flux

Coronal Magnetic Fields

- Direct Measurement of Coronal Fields is extremely difficult

- Direct Measurements are needed to verify theory and understand origins of solar flares and mass ejections



Sample Spectra

- Sensitivity of 0.1%
  - 150 Gauss Field Strengths
  - 1 Gauss Magnetic Flux
- Possible to use for Coronal Fields at 10747 A

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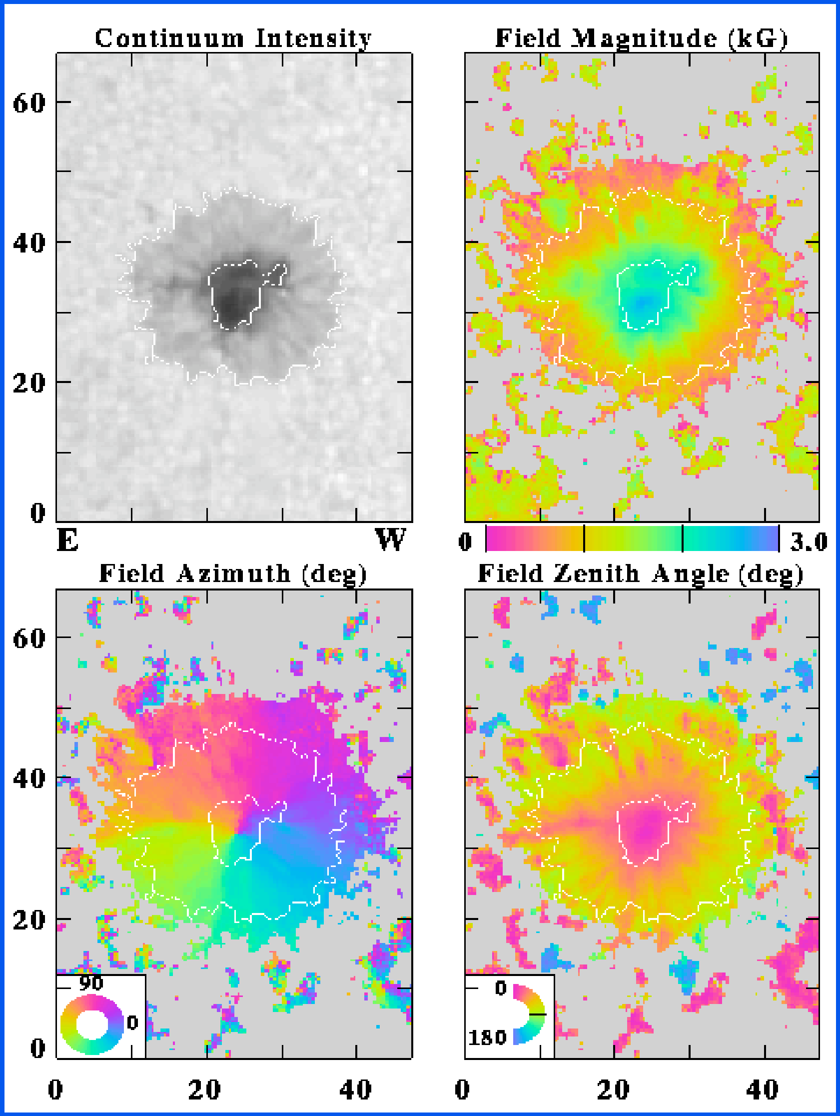
High Photon Flux



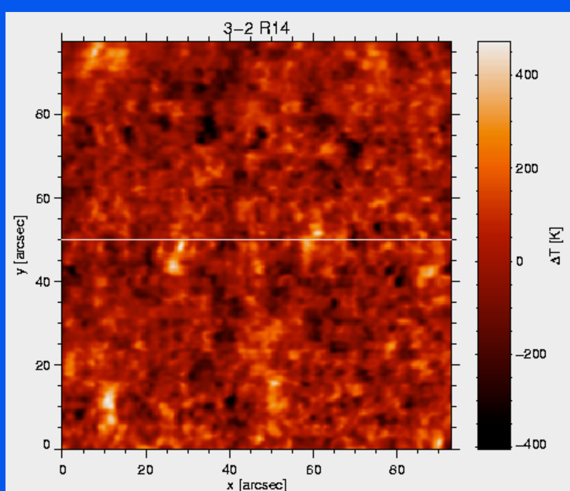
- Vector Polarimetery
  - 20må, SNR 2000, 10% Efficiency (Optimistic), 5 Positions, Visible
  - Need Several Minutes at Diffraction Limit (Independent of Aperture) Unacceptable
  - Evolution at Scales of 0.1 Arcsec Within 30s
  - Need 4m Telescope to Achieve SNR Within 30 S at 0.1 Arcsec Resolution

Data courtesy B. Lites

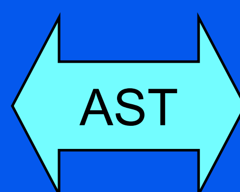
Advanced Solar Telescope

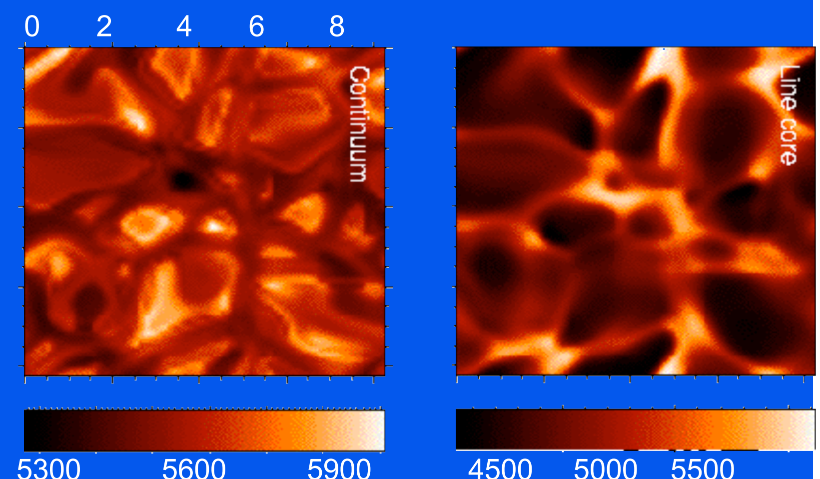
Thermal Infrared

- **General advantages:**
  - **LTE line formation**
  - **strong visible lines formed in upper photosphere and chromosphere are dominated by scattering, NLTE**
  - **clean way to measure thermodynamics and magnetic fields in higher atmospheric layers**
- **CO band at 4.8 μm:**
  - **text-book chromosphere exists almost nowhere on Sun**



Data courtesy D. Rabin & H. Uitenbroek





Model Courtesy of H. Uitenbroek

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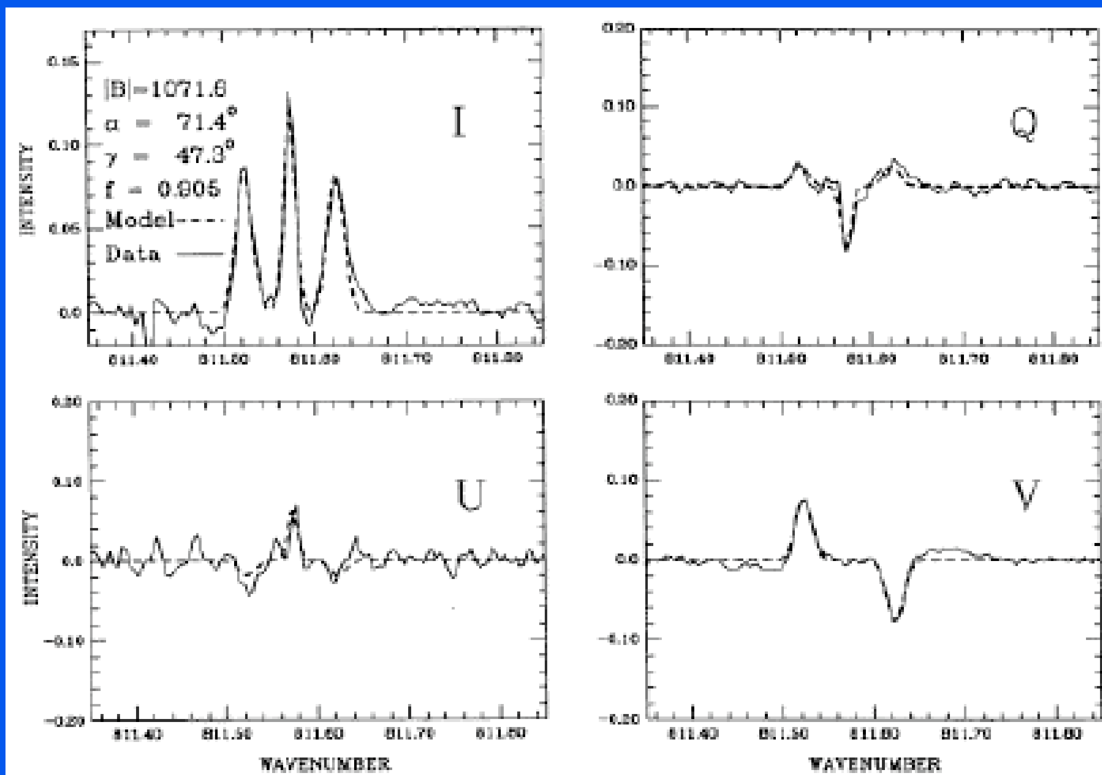
Thermal Infrared



Hewagama et al. (1993)

- **MgI at 12 μm:**
  - **model-independent vector fields in upper photosphere**
  - **more force free in higher layers, better suited for field extrapolation**
  - **sensitive to field strengths ~ 100 G**
  - **penetration of weak fields into higher layers**

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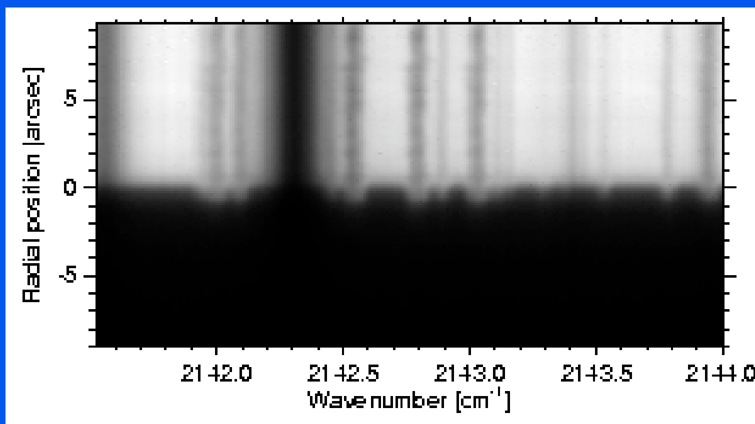
Chromosphere



- Goal: Observe and understand the structure and dynamics of the chromosphere

- Current state:
  - CO observations at 4.8 µm
  - OH observations near 11 µm
  - models of chromospheric dynamics
  - insufficient resolution and photon flux of McMath-Pierce: 1arcsec diffraction limit at 4.8 µm

- Future direction:
  - CO observations with high resolution and fast cadence
  - combination with other diagnostics in visible and infrared
  - provide 1arcsec resolution out to 12 µm
  - need large-aperture, all reflective telescope

Advanced Solar Telescope

Stepping stones towards AST

- Adaptive Optics Program at Dunn Solar Telescope → **AST Adaptive Optics systems**
- Infrared Program at McMath-Pierce Telescope and Dunn Solar Telescope → **AST Infrared Instrumentation**
- Open-air solar telescope tests; McMath-Pierce, CLEAR mock-up, DOT → **AST Open Telescope Seeing Control**
- Site testing program and evaluation of lake sites → **AST Site**

Advanced Solar Telescope

AST Considerations

- **Many Solar Observations Limited by Telescope Aperture**
- **Photon Mean-free Path, Pressure Scale Height in Photosphere ~70 Km, 0.1 Arcsec at Disk Center**
- **Magnetic Flux Concentrations ≤ 70 Km**
- **Diffraction Limit Is Not the Only Driver for Larger Telescope Aperture**
- **Diffraction Limited Resolution: $3 \cdot 10^8$ Photons/å/s in Visible, Independent of Aperture, Independent of Distance of Star**
- **Solar Structures Change Faster on Small Scales: 70 Km in 10-30s**
- **To Increase Photon Flux at Given High Resolution Need to Work Above the Diffraction Limit --> Larger Aperture**
- **Many Problems in Solar Physics Require New, Large-aperture (4m) Telescope With Adaptive Optics**

Advanced Solar Telescope

Some Design Issues

- **Development of High-order Adaptive Optic**
- **Open Telescope Concept**
- **Thermal Environment, Thermal Control**
- **High Energy Density in Primary Focus**
- **Minimize Instrumental Polarization**
- **Find Appropriate Site , Best Seeing Site**
- **Overall Telescope Design: RC Vs Gregorian, On-axis Vs. Off-axis, Active Primary or Light Weight, Adaptive Secondary?**

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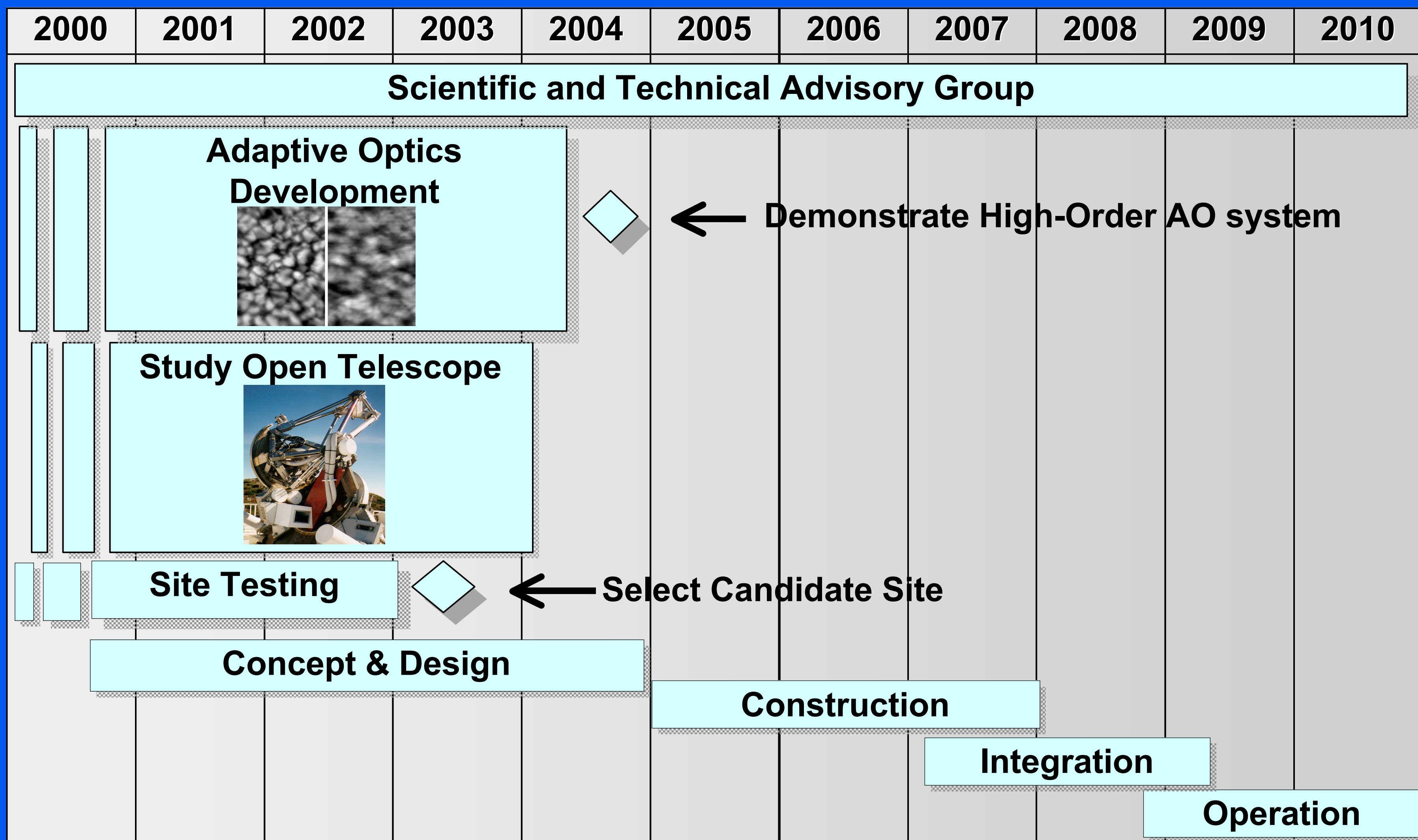
Timeline



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Implementation

- **Broad US Community and International Involvement**
  - **AST Workshop June 18, 2000 Prior to SPD Meeting at Lake Tahoe**
  - **Develop Concept & Design Phase Proposal**
  - **Telescope Work Packages**
  - **Instrument Work Packages**
  - **Site Surveys**

- **Phased Implementation**
  - **Concept & Design Phase 2001-2004**
  - **Manufacture & Construction Phase 2005-2007 (NSF MRE Proposal)**
  - **Integration & Commissioning 2007-2008**
  - **Operations 2009**

Advanced Solar Telescope

Outlook

- Science Requires Large-aperture (~4m), All Reflective Telescope With Adaptive Optics
- Sun Is Best Place for Testing Many Theories
- Solar Dynamo Is Paradigm of Stellar Dynamos
- Interaction of Convection and Magnetic Fields Are Best Studied on Sun
- All Spatial Scales on the Sun Interact in a Global Physical System
- Need Higher Spatial Resolution Than Offered by Current Telescopes
- Instruments Reach Limits of Current Telescopes
- Techniques Such As Speckle, Phase-diversity, Adaptive Optics Can Make Use of Large Apertures
- Spectroscopy and Polarimetry Are Photon Starved

Advanced Solar Telescope

Conclusions

- There Is a Strong Synergism Between the AST and the Living With a Star Initiatives
- They Enhance, Rather Than Duplicate, Observational Capabilities and Together Will Provide the Ability to Understand Solar Magnetic Activity
- The AST Will Provide a Test Bed for the Development of Future High-resolution Capabilities in Space and on the Ground

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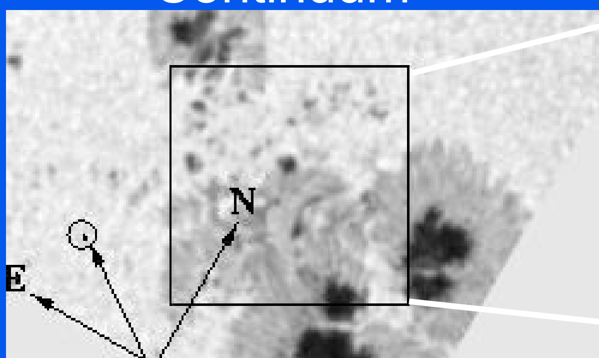
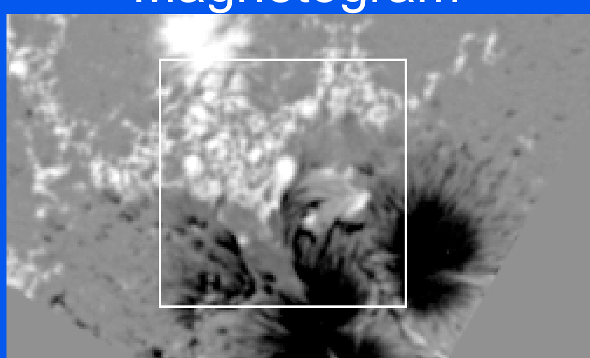
AST & LWS Synergism

SoHO/MDI

Continuum

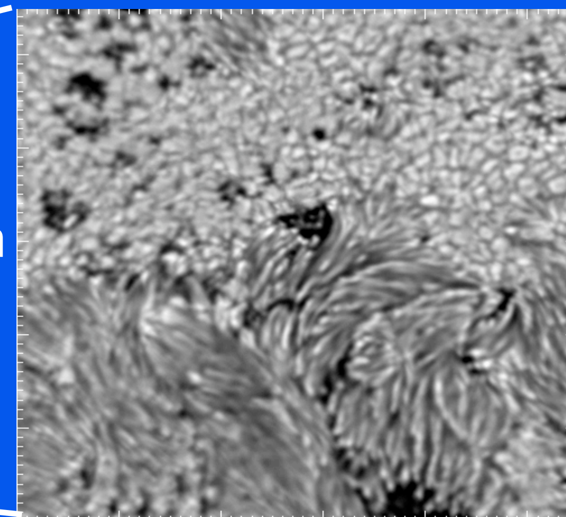


Magnetogram



Dunn Solar Telescope & AO

Continuum



Dopplergram